

Advanced Thermal Management for Military Application

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ABSTRACT

Today's coolant system consists mainly of technologies that have remained virtually unchanged for almost a century, yet modern day engines have advanced significantly in almost all other areas. A large amount of the engines horsepower goes into this antiquated and inefficient thermal system. Recent testing has shown that by properly controlling pumps, valves and fans, significant efficiency and emission improvements can be realized. Along with these benefits are improvements in packaging, life, and even operator comfort. These technologies can help the military decrease inventories, improve serviceability and decrease operating cost while increasing cooling capability. EMP has developed a family of products in order to help expedite this paradigm shift in thermal management. EMP, in partnership with the NAC, has successfully demonstrated these technologies on several military and commercial vehicles. This paper will summarize the products, systems and results to-date.

1.0 INTRODUCTION

Modern vehicles have some of the most advanced computer control systems and sensors in any industry. However, traditional approaches to engine thermal management usually involve a mechanical thermostat in conjunction with an engine driven water pump and fan. Thermostats are mechanical valves that use melting wax, which expands and moves the valve opening over a prescribed temperature band. Engine driven water pumps and fans are directly linked to the engine rpm and thus produce flow rates based on that rpm. These types of thermal controls are generally not very accurate, not controllable and lead to considerable parasitic losses. The need for higher fuel economy and tighter emission control standards over the last 20 years has forced improvements on many aspects of the engine and vehicle. However, there have not been many advances to the cooling system even though it manages a large portion of the engine energy output.

The benefits of better thermal management have been documented in several SAE papers over the last few years. These reports have shown that by electronically controlling pumps, fans and valves, thermal control can improve dramatically on both SI and diesel engines. When properly implemented, fuel economy improvements over 10% have been realized. These improvements come mainly from better temperature control and through decreased parasitic losses. Many other benefits can be obtained with such a system.

2.0 VEHICLE THERMAL LOADS

Typical vehicles have three areas where combustion energy is dispersed. About 40% goes to driving the wheels, 30% leaves through the exhaust and 30% leaves through the coolant system from vehicle thermal loads. This breakdown can change significantly when one considers the parasitic loss by components such as fans and pumps. It can also change depending on the driving cycle. Vehicle thermal loads are created through the conversion of chemical energy to thermal and mechanical energy and the transfer of that energy through the vehicle's powertrain. Vehicular thermal loading has increased due to higher power density, additional cooling loads from emission control devices, and additional components that require cooling. These trends will continue through the next rounds of emission regulations for 2007 and 2010. Packaging will also be important to account for these additional devices.

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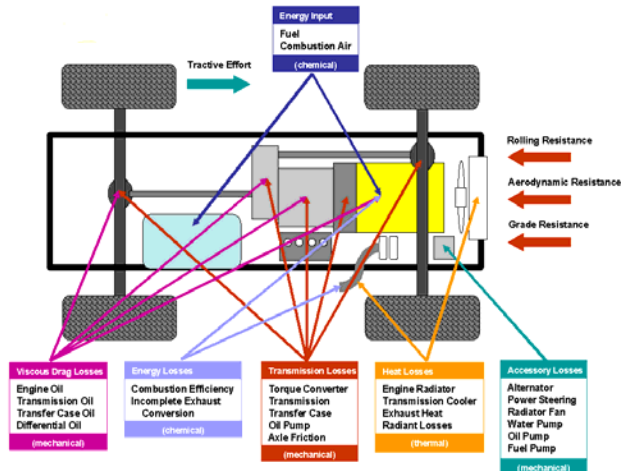


Figure 1: Energy loss breakdown

3.0 CONVENTIONAL COOLING COMPONENTS

Even with all the advancements in computer controls, modern day engine cooling systems are still configured similar to those almost 100 years ago. Issues with mechanically driven pumps in conjunction with a radiator were discussed as early as 1906. Thermostats similar to today's design date back prior to World War II. These types of mechanically based techniques have always had limitations.

The cooling system for a vehicle is comprised of several components that must work together to efficiently manage the vehicle's thermal loads. Each engine and vehicle manufacturer approaches the vehicular cooling designs differently, but most of the key components used are very similar. These components include mechanically driven pumps, thermostats, fans and heat exchangers. These systems are complex and have many linkages.

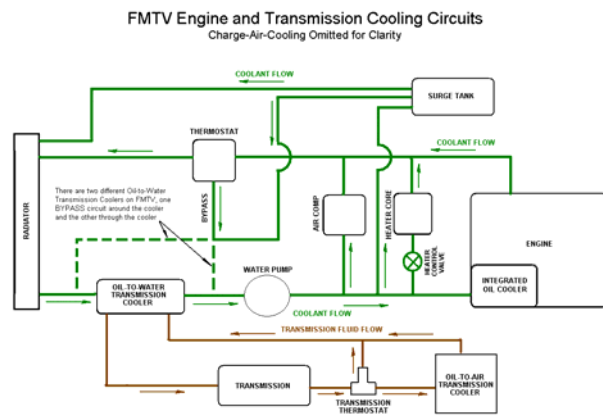


Figure 2: Diagram of typical TDI system

3.1 Coolant Pumps

Currently, mechanically driven by either belts or gears, coolant pumps are designed to circulate coolant through the engine. The drive on a standard pump links pump rpm and thus coolant flow to the engine RPM. Design points are usually based on the most extreme operating conditions. However, up to 95% of the time these pumps are producing much more (and sometimes less) flow than is required to maintain an optimal engine temperature. This is particularly true in high speed use where ram air is abundant or low speed operation where the air side is the limiting factor.

The belt and gear drive mechanisms put considerable load on the pump bearings forcing the use of large bearings and housings to support the loads. They have mechanical seals which are under varying cycle loading leading to premature failures. The drive mechanism tends to make the pump difficult to service in the field. Many military vehicles require the removal of the engine or other major components in order to change out the pump. To make matters worse, mechanical pumps are custom for a given engine and sometimes even vehicle model year. This drives up inventories and makes product sharing in the field very difficult.

3.2 Thermostats

Thermostats are a thermally actuated valve consisting of a wax that changes phase when heated. The valve restricts coolant from flowing to the engine radiator until the coolant temperature has reached a predetermined temperature corresponding to the melting point of the wax. Thermostats are single point control mechanisms that respond to the coolant temperature after exiting the block or head. Their response is slow, have unnecessary temperature fluctuations and lack accuracy. Thermostats are usually very restrictive causing additional parasitic losses.

3.3 Fans

The fan circulates air through the heat exchanger and over the engine. Fans are usually mechanically or hydraulically driven similar to the water pump and can sometimes have an on-off clutch. The process of pumping air is not very efficient and methods need to be developed to decrease fan on-time, improve system efficiency and offer controllability. Fans can draw well over 40 bhp in larger engines. Hydraulic fans can offer limited controllability but at the expense of extremely low efficiency and high weight. The use of a single large fan for cooling all the different circuits typically mean the fan is not effectively covering the area of the heat exchanger and sees considerable air-side pressure drop.

Also, the fan will turn on for any individual cooling circuit making it very difficult to optimize.

3.4 Heat Exchangers

These components are designed to transfer the thermal energy from one liquid or gas to another. Pressure drop on both sides of the radiator can add to parasitic losses for the fans and pumps. Heat exchangers can be used for not only the engine, but intake air (CAC), oil, transmission, HVAC, EGR, Electronics, hydraulics, etc. Selection, location and system integration are all important in the proper design.

3.5 Miscellaneous

There are essentially no diagnostics or prognostics available on these accessories. The first time an operator is aware of an overheating condition is usually when it is too late. Packaging is very difficult since the drive mechanism tends to restrict the placement of these components to the front of the engine.

4.0 ADVANCED THERMAL SYSTEMS

Considerable research has been done over the last 20 years to evaluate methods of electronically controlling various components. Advancements in computer control technology in the early 80's, developed for fuel injection and ignition, have made it possible to consider the benefits of adding controlled coolant flow. Electric valves, pumps and fans have been evaluated by many universities and companies across the globe with a wide range of success.

4.1 Electric Pumps

Many tests have been conducted with controlled coolant pumps. Controlled pumps have shown benefits in almost all conditions from cold startup to higher operating regions. Many studies have been conducted that show a conventional pump is producing the correct amount of flow only 5% of the time. This is typically during the severe design point where there are high loads and high ambient temperatures requiring maximum flow rate out of the pump. The objective is to give the engine and other systems only what is required to cool. High efficiency, ease of integration and robust electric pumps are required for the extreme environment of military applications. EMP has created a family of these pumps for both military and commercial use. These pumps are easy to integrate, maintain and can be commonized across many engines and vehicles.

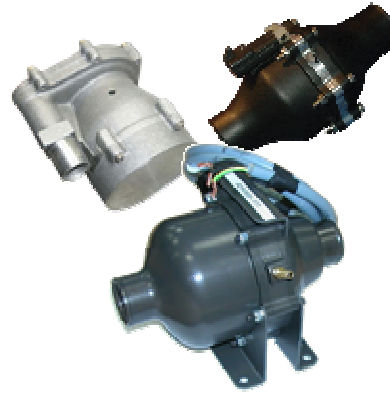


Figure 3. EMP electric water pumps

4.2 Electric Valves

As discussed earlier, conventional thermostats do not give precise control needed for future cooling systems. They are single point controllers only activated at a certain coolant temperature. Much work has been done with computer simulation and testing to evaluate the benefits of an electrically controlled thermostat. Many of these improvements have been in cold start and cold operating conditions. During these cold ambient conditions an electric valve could be used to raise the coolant temperature higher than with a conventional thermostat and still satisfy the engine needs at high thermal load situations. In this manner the engine can run warmer than normal which can help enhance combustion along the walls, improve heat flow return and obtain higher combustion temperatures. Low restriction, robust valves are required for military applications. Again EMP is creating a series of valve sizes for commercial and military applications.



Figure 4. EMP electric valves

4.3 Electric Fans

It is not practical or efficient to electrify a single electric fan that may require over 40 h.p. worth of energy. However, smaller targeted diesel grade fans could be used to break out individual cooling loads, with better coverage and redundancy than a single mechanical fan. Several small cost effective fans could be used on a given heat exchanger.

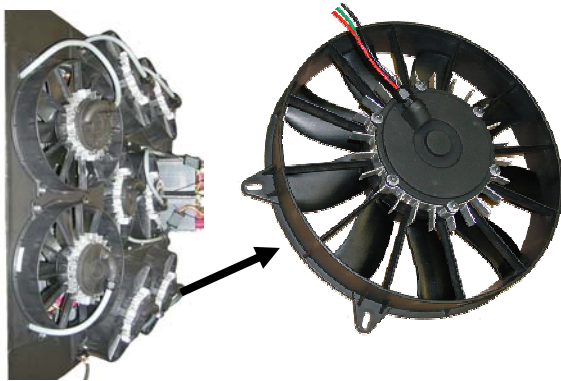


Figure 5: Fan module with EMP “Diesel Grade Fans”

EMP is creating a series of militarized electric fans which can handle the extreme environments, are efficient and fully controllable. Also, they can offer fan reversal for heat exchanger clean-out.

4.4 Enablers

The electric powered cooling components have been talked about and experimented with for years. However, a practical way to implement them has only recently been possible. Many factors have led to the development of production ready components. These include robust controllers, higher voltage, low cost digital signal processors, efficient electric motors and computer simulation tools.

5.0 BENEFITS - ADVANCED THERMAL SYSTEMS

The key benefits of electronic accessories include decreased parasitic power loss, improved heat management, decreased exhaust emissions, improved reliability, and flexibility in component packaging. Significant fuel economy improvements are achievable with a well-implemented system.

5.1 Reduced Parasitic Loss

Parasitic power losses for pumps and fans are finally well understood. There are many ways to reduce the loss during component design and system integration. These include:

- Packaging flexibility means fewer compromises must be made in the component design.
- Decrease drive losses by eliminating mechanical drive systems.
- Decrease pumping losses by operating pumps at optimal points.
- Reduce friction by controlling the engine temperature to a higher level.
- Reduce system pressure drop thru less restrictive valves and by decreasing hose loss.

5.2 Improved Thermal Control

Precise thermal control is crucial for operation of an engine at its optimal condition as it allows for higher combustion temperatures. The benefits include:

- Elimination of overcooling during part load operation by controlling cooling flow.
- Eliminate hot soak after shutdown by circulating coolant through the engine.
- Allow for quicker engine warm-up by slowing or stopping coolant flow during cold start.
- Thermally optimize engine by increasing average combustion temperature.
- Increase lubricant life by better oil temperature management.

5.3 Decreased Emissions

Changes in engine emission regulations are driving engine technology development. A designer can have the most fuel efficient, compact, and versatile engine in the world, but if it does not meet the mandated emission requirements, the engine can't be sold. With that understood, here are some ways an advanced thermal management system can help the engine designer meet their emission goals:

- Increased fuel economy decreases overall quantity of emissions, especially CO₂.
- Better control of diesel intake air temperature and combustion chamber temperature may allow optimization of the injector spray pattern to reduce HC and particulates.
- Reduced engine warm-up time decreases hydrocarbon and CO₂ emissions.
- Improved temperature control enables the use of a more optimal engine calibration.

5.4 Increased Life

Some additional benefits of controlled cooling technology can be extended engine life. These benefits may be difficult to quantify in the short term, but the changes in engine operating characteristics lend themselves to extended engine and component life.

- Reduce engine wear by running key components at their design points.
- Reduce thermal stress on engine through tighter temperature control.
- Limit the thermal stresses on components after shutdown by eliminating hot soak.
- Decrease wear by reducing engine warm-up time.
- Driving components with electric motors reduces bearing loads improving component mechanical life.

5.5 Improved Packaging Flexibility

System flexibility is a major positive attribute of the controlled cooling concept since electrically-driven components need not be mounted on the front of the engine. Consider the following reasons that make the system almost universal to all engines.

- Remote mounting of components for easier serviceability.
- Distributed cooling with electric fans as opposed to a heat exchanger module stack concentrated in front of a mechanical fan.
- Commonization of components across engine families and vehicle model years to reduce parts inventories required to support fleets.
- Decrease overall package size by optimization and configuration flexibility.

5.6 Diagnostics & Prognostics

With electronically controlled components, it is now possible to assess the condition of the components and system while the engine is operating. Not only is it possible to alert the driver to a potential concern, but information can also be gathered by fleet operators to aid in scheduling vehicle maintenance.

6.0 EXAMPLE MTTD

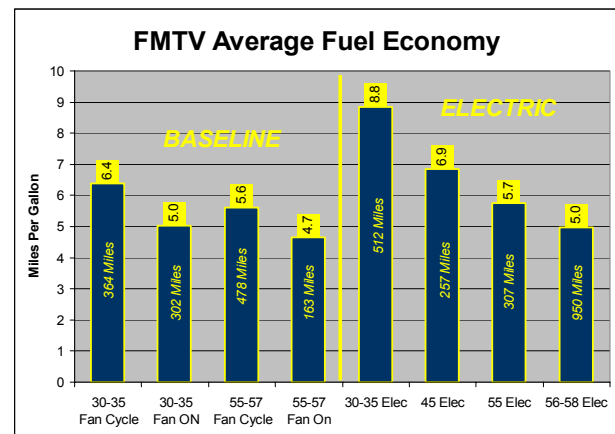
EMP has two projects involving the thermal management of a Stewart and Stevenson FMTV to improve the vehicle cooling systems while improving vehicle fuel economy. The first vehicle was used to demonstrate the reduction in parasitic energy consumption through the electrification of cooling and lubrication system components. The second program used the FMTV as a mule to develop an electrically

powered confined space cooling system and show the benefits in thermal control and overall vehicle efficiency.

Baseline data was collected under both programs and compared to the electrified systems thermal performance and fuel economy. The major differences in the two programs were the packaging and configuration of the cooling systems.

The parasitic program packaged an electrically driven engine cooling pump, an electrically driven transmission cooling pump, an electronically controlled thermostat, and an array of electrically driven fans on the current radiator. This vehicle was field tested with cooling system performance and fuel economy being monitored. The fuel economy data is presented in the following figure with the number of miles traveled under each operating condition.

Table 1: FMTV fuel economy – Parasitic loss study



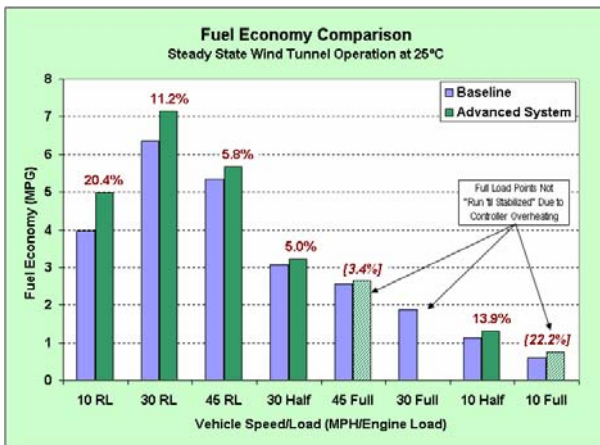
The benefits were greatest at the lower vehicle speeds where the cooling system power consumption is a larger percentage of the overall vehicle power requirements. The transmission also operated at a higher and more stable temperature reducing the viscous drag. Engine thermal control improvements and a 5.5 kW fan power reduction were also realized.

In the second vehicle, the confined space thermal management system replaced the vehicle heat exchangers with modules that mounted behind the cab of the vehicle. It utilized electric pumps, radial flow fans, and an air-to-water charge air cooler in addition to control valves. The vehicle was tested on a chassis roll dynamometer in an effort to generate repeatable load and fuel test data. The data is presented in the table below and shows peak fuel economy improvements of over 20%! Also improved temperature control and decreased warm-up were realized.



Figure 6: Confined space cooling system behind cab

Table 2: Confined space thermal system fuel economy



Although the systems in the two vehicles differed significantly in configuration, control strategies, and evaluation processes, both programs showed the largest improvements at low speed operation. Also, both vehicles demonstrated significant fuel economy improvements and better thermal system control.

7.0 EXCURSION WITH 6.0L TDI

A Ford Excursion with a 325 hp 6.0L diesel was selected as a light duty platform to demonstrate advanced thermal management to efficiently manage heat loads and improve fuel consumption. Although the fuel consumption rate per vehicle is lower than for medium and heavy vehicles, the large number of light duty vehicles accounts for a significant amount of fuel consumption and logistical supply demands.

The cooling system of the base vehicle consists of a 2.9 hp mechanical water pump and 28.5 hp electronically controlled viscous clutch fan. The cooling module is a stack of 4 heat exchangers, composed of an A/C condenser, air-oil transmission cooler, air-to-air charge air cooler (CAC), and radiator. This arrangement is typical of a modern light duty truck. There is also an additional oil-liquid transmission cooler in the radiator end tank and an EGR cooler in the valley of the engine. As truck design has progressed toward cab-forward designs and more equipment has been placed in the engine compartment, there is reduced space for under-hood cooling airflow. However, heat rejection continues to rise as engine power ratings increase and 2004, 2007, and 2010 emissions limits require technology such as EGR which further increases heat rejection. Thus, even though light duty diesel vehicles can benefit from some ram air cooling, the cooling is limited by the air mass flow through the restrictions of the heat exchanger stack and extremely tight under-hood space.

The advanced system addresses the limitations of the base vehicle by distributing the cooling loads and allowing for individual cooling control of the jacket water, charge air, EGR, transmission, and air conditioning. A radiator for EGR cooling is located behind the left side of the bumper, and ahead of the wheel well, which yields a greater overall frontal area for heat rejection, while shielding the EGR radiator and 11" EMP fan from debris. A 3 pass counter-flow oil-air transmission cooler and 11" fan is located on the opposite side of the vehicle. Semi-cooled EGR is combined with the turbo-out air, and the combination is cooled by a water-cooled CAC on a separate low temperature coolant loop controlled by an EMP electric water pump. A low temperature (LT) radiator (of 16% less core area and 35% less total area than the base CAC), sits between the frame rails, and a compact flat-tube condenser fits above the LT radiator and over the frame rails. The radiator, shroud, and electric fans reside behind the LT radiator and condenser. This reduction in heat exchanger package space results in the radiator position being located 7.75" ahead of the base radiator position, which met the objective of freeing up under-hood space for increased airflow. Engine cooling is provided by two 12V electric water pumps and an electric control valve.

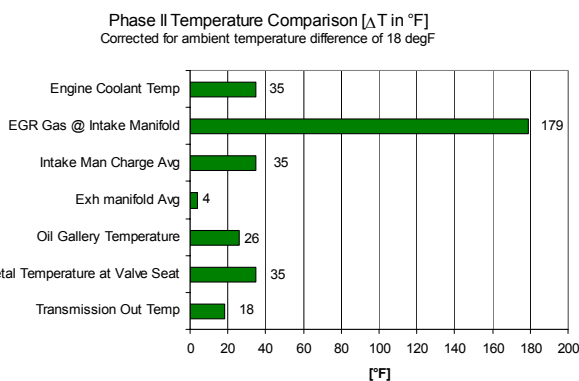
With this configuration, cooling system parasitic losses are decreased from 23.5 kW to 3.6 kW (31.5 to 4.8 hp), as shown below with the breakdown of fan power and water pump power.

Table 3: Cooling system power consumption.

	Mechanical Cooling System	Electric Cooling System *
Fans(s)	21.3	2.3
Pump(s)	2.2	1.3
	23.5	3.6

Road and trailer tow tests have shown an improved ability to reject heat and control engine oil, coolant, intake manifold, EGR, and transmission temperatures. With the improved under-hood airflow and high efficiency controllable water pumps, the advanced system can maintain system temperatures at a lower level during full load testing (table 4), thus demonstrating the ability to readily reject heat under high ambient and high load conditions, which is a challenge for all vehicles. Further testing will be done to determine the affects on fuel economy.

Table 4: Cooling system performance from trailer tow tests.



7.0 VEHICLES AND SYSTEMS OF THE FUTURE

When considering the vehicles and thermal management systems of the future, where will the advances be made? Vehicles will be designed to consume less energy to complete the same tasks they do today. This will be completed by reducing vehicle dynamic loading, reducing powertrain losses, and increasing the efficiency of all other vehicle systems. Systems including “regenerative braking”, “waste heat recuperation”, “belt-less cooling” and “hybrid powertrains” will define the vehicular landscape.

Consider control of all thermal loads on the engine. The system may contain full distributed cooling. With a controllable cooling system for the primary engine cooling, the EGR system, the transmission, engine oil and the charge-air-cooler, the engine designer now has

full control of all the temperatures in the vehicle. Each system, now controlled independent of engine speed or load can be fitted on a vehicle as individual modules. This can allow for maximum optimization and flexibility.

Powertrain modifications and vehicle accessories are other sources of potential efficiency gains. Efficiency gains are driving the Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) along with the potential to eliminate or reduce mobile vehicle emissions. Hybrid vehicles still require a mobile energy source to generate and store the electric energy required to propel these vehicles. Generation alternatives include diesel or gas generators and fuel cells with other energy sources. Hybrids are a good source of efficient power to electrify components such as fans, pumps and valves. Voltages being discussed typically include 340 VDC and over.

Fuel cells have their own thermal management issues with heat rejection rates several times more than that of combustion engines. Also, they have lower operating temperatures reducing the temperature differential between the coolant and the ambient. This will tend to increase the size and power requirements of the cooling system. Creativity in design and packaging will be a must.

8.0 CONCLUSION

The time has come to update engine and vehicular thermal management systems for the 21st Century. The needs of military and commercial industries are changing. Emissions and fuel economy are becoming important as heat rejection continues to increase. Both military and commercial vehicles will benefit from such an approach. The drivers are in place, the sensors are already on the vehicle, and efficient electric power sources are nearing production. The controllable electric pump, valve and fan technologies will serve more than just engine thermal management. It will be applied in EVs, Fuel Cells and HEVs where mechanical drive means may not exist. They will cool and lubricate traction drive motors, cool power electronics, and be integral in battery and capacitor thermal management. Electric pumps, fans and valves will provide efficiency gains over conventional components, be flexible to operate in several different systems, and can be remote located anywhere in the system. Electronic thermal management systems will be one of the most beneficial areas of engine and vehicle development over the next decade.

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